



Development of Operational Protocols for Electric Barrier Systems on the Chicago Sanitary and Ship Canal: Induction of Passage-Preventing Behaviors in Small Sizes of Silver Carp

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PURPOSE: The Chicago Ship and Sanitary Canal (CSSC) is a navigable channel that connects Lake Michigan to the Mississippi River Basin. Electric barrier systems have been constructed to create waterborne electric fields within the CSSC to prevent Asian carp from swimming from the Mississippi River basin through the canal into the Great Lakes. A laboratory study was conducted to determine which characteristics of the waterborne electric fields of pulsed direct current (pulsed DC) are effective at immobilizing (preventing passage of) small Asian carp that enter the electrified zone. This experiment was the first step in a comprehensive study to determine optimum operating parameters for electric barrier systems in operation to prevent dispersal of aquatic nuisance species — including Asian carp — through the CSSC and other aquatic systems.

SUMMARY: The goal of this experiment was to determine an operating protocol for Electric Barrier System IIA in the CSSC. The operating protocol for the Barrier IIA needs to be effective in preventing passage of Asian carp through the electrified zone in the Canal. The electrical conditions within this electrified zone, with the System operating under various output protocols, were simulated in a tank and the responses of captured, wild juvenile silver carp *Hypophthalmichthys molitrix* during and after the electrical exposures were monitored. Fish used in the experiment were between 5.4 – 11.0 inches (137 - 280 mm) total length. Combinations of pulse duration (milliseconds; ms), pulse frequency (hertz; Hz), and field strength (volts/inch; V/inch) were tested, three of which proved effective in stunning all fish in each treatment during the 24-second exposures. Outcomes indicated the operational protocol in use at the time (i.e., 4 ms pulses delivered at a rate of 5 Hz at a maximum surface field strength of 0.4 V/cm) to be insufficient for blocking passage of these fish through the electrified zone. Therefore, the most effective combination of 15 Hz pulse frequency, 0.79 V/cm, 6.5 ms pulse duration for fish greater than 200 mm was subsequently incorporated into operation of Barrier IIA later in 2009 and served as the basis for future testing.

BACKGROUND: The CSSC was constructed for wastewater management and shipping access between the Great Lakes and the Mississippi River Basins (via the Illinois River System). It is the only direct connection between the two basins, and as such, can serve as a conduit of dispersal for aquatic invasive species. Species of concern include round goby *Neogobius melanostomus* and zebra mussel *Dreissena polymorpha* moving from the Great Lakes into the Mississippi River Basin (Charlebois et al. 1997). From the other direction, Asian carp, particularly bighead carp *Hypophthalmichthys nobilis* and silver carp *H. molitrix*, have established reproducing populations in the Mississippi River System and threaten to move into Lake Michigan via the CSSC (Stainbrook et al. 2005; Figure 1).

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Figure 1. Four species of Asian carp (from top to bottom): bighead, silver, grass, and common carps.

The U.S. Army Corps of Engineers (USACE) Chicago District operates a series of electric barrier systems on the CSSC to prevent the transfer of aquatic nuisance species between the two basins (Figure 2). The barriers were initially constructed to prevent movement of round gobies and other invasive species from the Great Lakes into the Mississippi River Basin, but later operated to contain Asian carp moving up the Illinois River towards Chicago. The most upstream electric barrier, developed as a demonstration project, has been in operation since April 2002. Electric Barrier Systems IIA and IIB, the second and third systems constructed on the CSSC, can generate larger and more intense electric fields than the demonstration electric barrier system, with electrified zones extending about 44 meters (m) in the upstream-downstream direction. Barrier IIA began operation in 2009 and Barrier IIB began operation in April 2011. A larger, permanent barrier with even greater capacity than Barriers IIA and IIB is under construction. These three barriers are the largest electric barriers across a navigable waterway in the world.

DESCRIPTION AND OPERATION OF ELECTRIC BARRIER SYSTEMS: Electric barrier systems have three primary components: the physical structure, the electrodes, and the power supply (Sternin et al. 1976). The physical structure typically houses the electrical power supplies and accessory systems and the backup power supplies; the physical structure also anchors electrodes. The electrode arrays provide the interface between the onshore electrical power systems and the environmental water. Most early electric barriers employed vertical, hanging electrodes, but bottom-mounted, cable-like electrodes have become more common (Hunn and Youngs 1980; Swink 1999). The electric barrier systems operating on the CSSC employ cross-channel, bottom-mounted electrode arrays. Early electric barriers typically applied single- or three-phase alternating current (AC) to guide or block passage of fish. In the 1950s, pulsed DC was found to be effective in immobilizing fish (Halsband 1967) and replaced or augmented the use of AC, sometimes to prevent or reduce fish mortality (McLain 1957; Hunn and Youngs 1980). The electric barrier systems operating in the CSSC convert commercial AC to pulsed DC for output by the electrode arrays submersed in the canal.

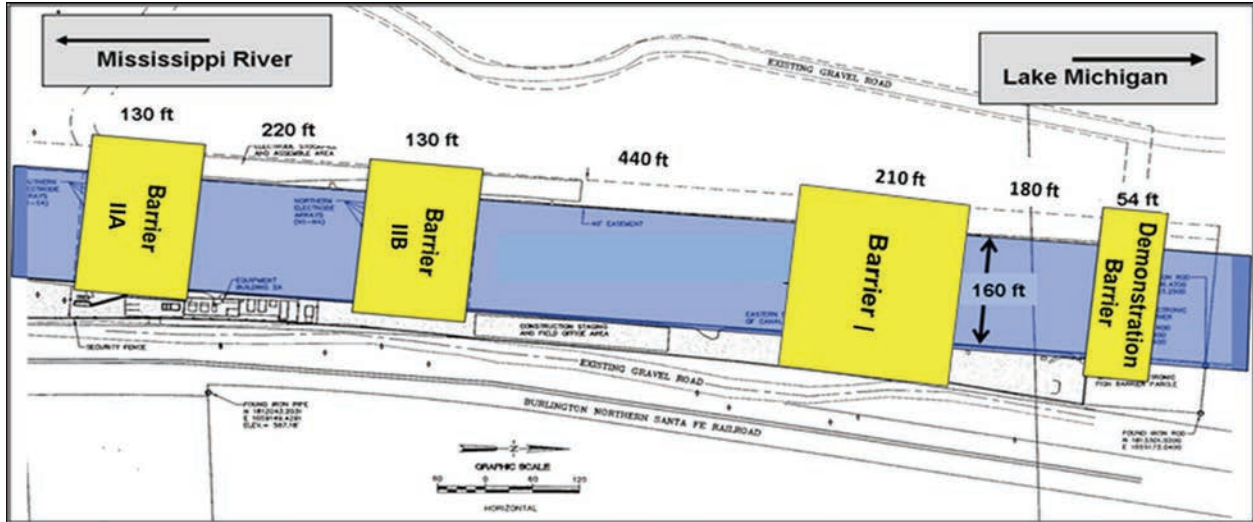


Figure 2. Map showing the location of electrified zones on the CSSC generated by the electric barrier systems to prevent passage of aquatic nuisance species. From USACE Chicago District.

Electric Barrier Systems incorporate environmental water into an electrical circuit composed of conductors (the submersed electrodes) and a source of electrical energy (the onshore power supply). In this circuit, environmental water serves as a path for electrical current flow and as a “load” (resistance) for the circuit. When the circuit is closed, the onshore power supply creates a difference in electrical potential between submersed electrode arrays and flow of electric current in the system’s conductors and electrodes creating a waterborne electric field. The quantity of electric current flowing through the circuit is determined by the voltage applied to the electrodes and the resistance experienced by the circuit, which is directly related to the ability of the environmental water to conduct electricity (that is, the conductivity of the water). The conductivity of the water is determined by ion concentration (the charge carriers) and temperature. Electromagnetic forces of attraction and repulsion, the local environment, and characteristics of the electrode array (e.g., electrode orientation, size, and spacing) determine the distribution of electric current (the electric field) in the water. In general, the strength of the electric field decreases with distance from the electrodes in both the vertical and horizontal aspects.

The potential difference (voltage), and the pulse frequency and pulse duration of the DC pulses applied to the submersed electrodes can be used to characterize the electrical output of the electric barrier systems. The characteristics of the pulsed DC applied to the electrodes are directly reflected in the waterborne electric field. The intensity of the waterborne electric field (i.e., field strength), which can be measured as the voltage change per unit distance (i.e., voltage gradient, volts/centimeter (V/cm)), is directly proportional to the voltage applied to the electrodes. The rate at which the waterborne electric field pulses (measured in cycles per second (Hz)) and the duration of each pulse (the pulse duration, measured in milliseconds (ms)) is determined by the pulsed DC applied to the electrodes.

Electric barrier systems are regarded as behavioral technologies that function by using waterborne electric fields to induce avoidance and immobilization responses in fish to block passage or direct movement. There is a long history of using waterborne electric fields in fisheries management (e.g., McMillan 1928), but there are relatively few published evaluations on the effectiveness of these systems. There are even fewer published accounts of comparative tests of the electrical parameters

employed by the systems. The design and operation of electric barriers are often site, species, and circumstance specific (Stewart 1990). The individuality of the systems and their operations may render available information inapplicable to other facilities (Johnson et al. 1990), driving the present need for research specific to the electric barrier systems being operated in the CSSC.

METHODS: In April 2009, a study exploring the effectiveness of combinations of waterborne electric field characteristics for blocking passage of invasive Asian carp through the CSSC was conducted. Wild silver carp were captured with seines below the Bonnet Carre Spillway, LA and transported to the Aquatic and Wetlands Ecosystems Research and Development Center at the (USACE) Engineer Research and Development Center (ERDC) via hatchery transport trucks and tanks. Fish were held in closed, water-recirculating aquaculture systems (Figure 3) prior to use in the experiment the following day.



Figure 3. Recirculating aquaculture systems housing silver carp prior to testing.

Estimates of the voltage, pulse duration, and pulse frequency output capabilities of Electric Barrier System IIA were needed to ensure that the electrical exposures applied in the experiment would be applicable to operations in the CSSC. A software application was developed to estimate the maximum pulse duration that Electric Barrier System IIA could sustain when generating voltages necessary to achieve maximum in-water, surface field strengths that ranged from 0.2 to 1.9 V/cm, in increments of 0.2 V/cm, and pulse frequencies that ranged from 0.1 to 40 Hz (in increments of 0.1 Hz). Constraints in the application included a peak electrical output of 1.5 Megawatts and the maintenance of appropriate levels of electrical current and charging times for the power supply capacitor bank. The outcomes of the simulation were used to select combinations of electric field characteristics applied in the experiment.

Fish were exposed to electrical treatments in a 213 cm x 61 cm x 56 cm fiberglass tank outfitted with identical stainless steel plate electrodes (Figure 4). The electrodes were positioned parallel, extended above the water surface, and covered the entire cross-sectional area of the tank, thus generating a homogeneous electric field (Holliman and Reynolds 2002). A customized Model BP-1.5 Programmable Output Waveform (POW) Fish Barrier Pulsator (Smith-Root, Inc., Vancouver, Washington) served as the power supply for the exposure tank.



Figure 4. Exposure tank, electrodes, and power supply employed in the electrical exposures.

Electrical treatments were administered to fish individually (one at a time). The treatments were applied as a series of eight exposures to pulsed DC, characterized by combinations of voltage, pulse frequency, and pulse duration, each lasting three seconds. Voltage gradient increased with each exposure in the series for a cumulative exposure of 24 seconds. Hoover et al. (2012) reported maximum burst speeds of subadult silver carp (141 to 288 mm TL) of 128 cm/s and 166 cm/s for subadult bighead carp (250 to 334 mm TL). Konagaya and Cai (1987) estimated the maximum economic swim speed of silver and bighead carp (fish size was not provided) to lie below 200 cm/s (or ~6.6 feet/s). Fish swimming at this speed would traverse the width of an electrified zone in approximately 20 to 26 seconds. The cumulative period of the electrical exposure in a treatment was 24 seconds. However, the three-second electrical exposures were interrupted by 2 to 3 seconds of no electrical exposure, the time required to adjust the voltage applied in the exposure.

Fish behavior was visually monitored and recorded during and after each electrical exposure. The series of electrical exposures comprising a treatment were terminated if the fish being tested became incapacitated (i.e., immobilized; indicated by tetany, loss of equilibrium, cessation of swimming movements). Fish response was reported as a cumulative percentage (%) of fish within each experimental group incapacitated (immobilized) at each of the levels of field strength applied in the treatments. Ambient water conductivity was between 687 and 765 $\mu\text{S}/\text{cm}$ during the tests. Water temperature was between 21.1 and 23.3 $^{\circ}\text{C}$.

RESULTS: Electrical treatment selection was based on estimations of Barrier IIA output capabilities (Figure 5). Interactions were demonstrated between the maximums of pulse length, pulse frequency, and field strength that Barrier IIA can sustain. Field strengths greater than 1.5 V/cm in the treatments, exceed the present capabilities of Barrier IIA.

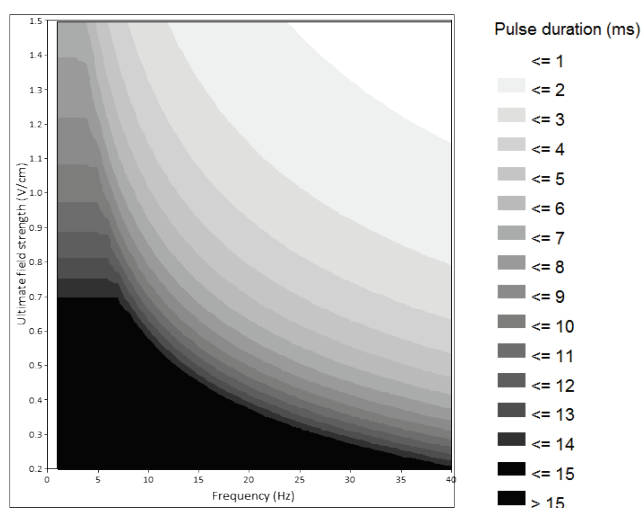


Figure 5. Barrier IIA output capabilities. Contours of estimated maximum pulse duration (ms) and field strength (volts/cm) that can be sustained by Electric Barrier System IIA, as a function of the pulse frequency (Hz), is shown. The estimated output capabilities of Barrier IIA were used to guide selection of electrical treatments applied in the pilot experiment on small silver carp.

Pulse frequencies applied in the electrical treatments equaled (5 Hz) or exceeded (10 Hz, 15 Hz) that being used in the canal at the time of the experiment. The pulse lengths applied in the electrical treatments ranged from 1.6 to 24 ms. The range of field strengths applied in each treatment depended on the estimated maximum output capabilities of Barrier IIA for that pulse length and frequency combination. Maximum field strengths for some treatments were selected to exceed the capabilities of the Electric Barrier System when field strengths within the present barrier capabilities proved inadequate for stunning fish (Table 1).

Table 1. The electrical treatments (in-water field strength (volts/cm) associated with the DC pulse lengths (ms) and frequencies (Hz)) evaluated in the study on juvenile silver carp.

5 Hz			10 Hz				15 Hz		
4.8 ms	8.9 ms	13.8 ms	2.4 ms	4.3 ms	9.8 ms	24 ms	1.6 ms	2.9 ms	6.5 ms
0.4	0.3	0.2	0.4	0.3	0.2	0.1	0.4	0.3	0.2
0.6	0.4	0.3	0.6	0.4	0.3	0.2	0.6	0.4	0.3
0.8	0.6	0.4	0.8	0.6	0.4	0.2	0.8	0.6	0.4
1	0.7	0.4	1	0.7	0.4	0.3	1	0.7	0.4
1.2	0.9	0.6	1.2	0.9	0.6	0.3	1.2	0.9	0.6
1.3	1	0.6	1.3	1	0.6	0.4	1.3	1	0.6
1.6	1.1	0.7	1.6	1.1	0.7	0.4	1.6	1.1	0.7
1.9	1.4	0.9	1.9	1.4	0.9	0.5	1.9	1.4	0.9

The response of silver carp to electrical exposure was evaluated in 80 fish (eight fish per treatment). Fish used in the experiment were 137 to 280 (average \pm SD; 195 ± 35) mm total length and weighed from 20.3 to 469 (73 ± 63) grams (Figure 6). Cumulative percentage of fish stunned during the electrical exposures varied markedly among the treatments (Figure 7).

Electrical treatments employing DC pulses of 4.8 ms, 8.9 ms, and 13.8 ms duration at a frequency of 5 Hz and field strengths of 0.4 to 1.9 V/cm, 0.3 to 1.4 V/cm, and 0.2 to 0.9 V/cm stunned 38%, 63%, and 25% of fish, respectively. Of the four electrical treatments utilizing 10-Hz pulses of DC (2.4 ms duration, 0.4 to 1.9 V/cm; 4.3 ms duration, 0.3 to 1.4 V/cm; 9.8 ms duration, 0.2 to 0.9 V/cm; and 24 ms duration, 0.2 to 0.5 V/cm), only the 2.4 ms pulses at a frequency of 10 Hz treatment stunned all fish in the treatment (Figure 7). The field strength required for 100% effectiveness with 2.4 ms pulse lengths and 10 Hz exceeded the theoretical upper limit for field strength for the electric barrier.

All fish (100%) in each of the treatments utilizing DC pulses of 15 Hz (1.6 ms, 0.4 to 1.9 V/cm; 2.9 ms duration, 0.3 to 1.4 V/cm; 6.5 ms duration, 0.2 to 0.9 V/cm) were stunned at field strengths within the output capabilities of Barrier IIA (Figure 7). All fish exposed to 24 ms pulse duration at a 10 Hz frequency (the treatment applying the lowest field strengths of those tested) exhibited escape or avoidance behaviors when exposed at 0.15 V/cm, but no response or twitch was induced in 63% of those exposed to 0.12 V/cm (the lowest level applied). This could indicate a field strength threshold for an escape/avoidance response. Vigorous flight behaviors were demonstrated by all fish exposed to the lowest levels of field strengths applied at the other pulse durations and frequency combinations, including the most effective treatments.

DISCUSSION: Experimental outcomes showed that risk for failing to immobilize fish encroaching upon the electrified zones in the CSSC will be strongly influenced by the operational protocol applied in the simulations. The operational protocol applying voltage to achieve a maximum surface voltage gradient of 0.79 V/cm, at a pulse frequency of 15 Hz, and pulse-duration of 6.5 ms was shown effective for immobilizing small silver carp (137 to 280 mm total length) and was recommended for use at Barrier IIA. At the time of the experiment, the Electric Barrier System IIA was being operated to achieve maximum field strength of 0.4 V/cm, at a pulse frequency of 5 Hz, and pulse duration of 4 ms. The operational protocol for the IIA Electric Barrier System was changed to the recommended protocol in 2009 and served as the basis for future testing, particularly on fish smaller than 200 mm TL.

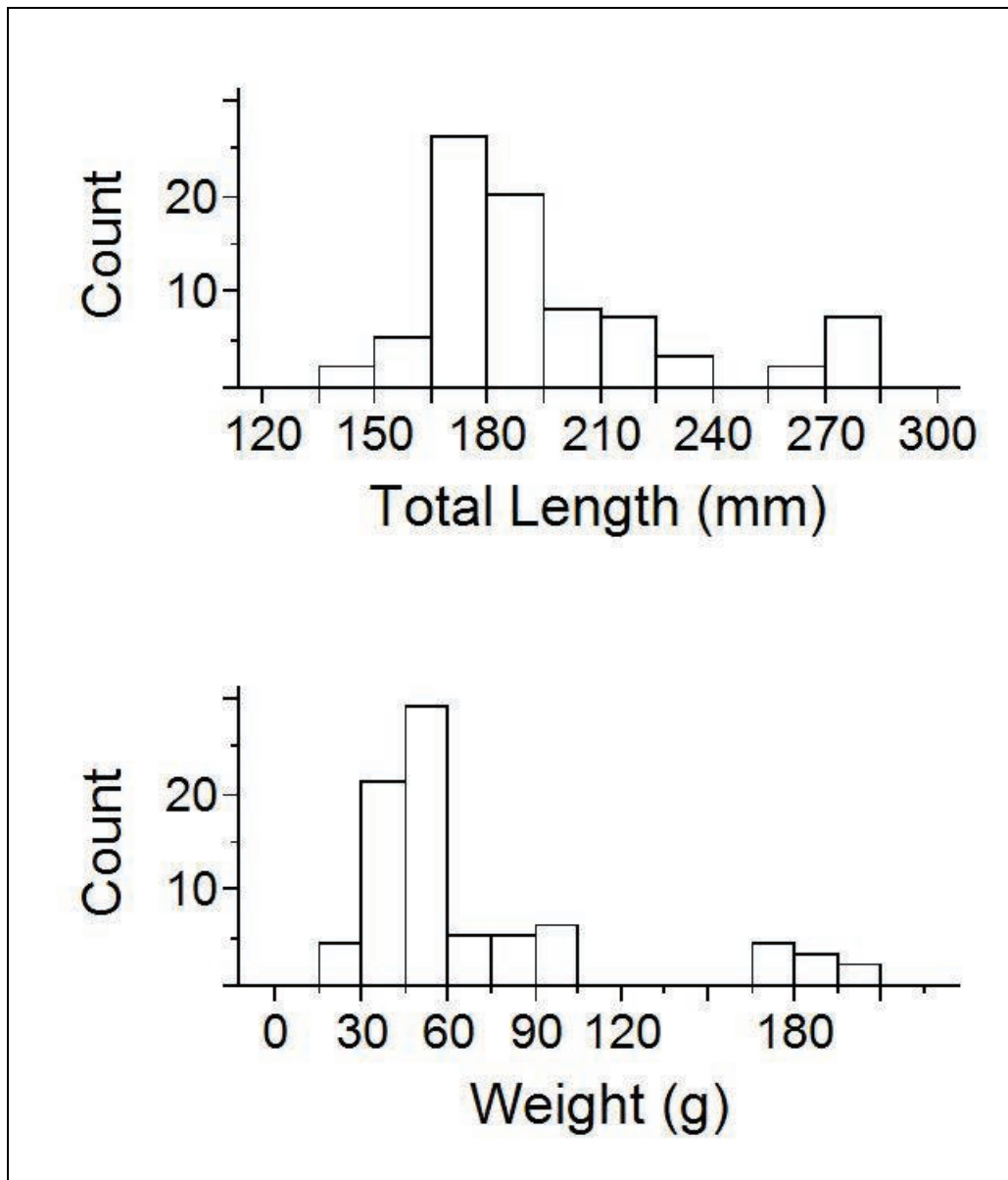


Figure 6. Histograms of total length (mm) and weight (g) of silver carp used in the study.

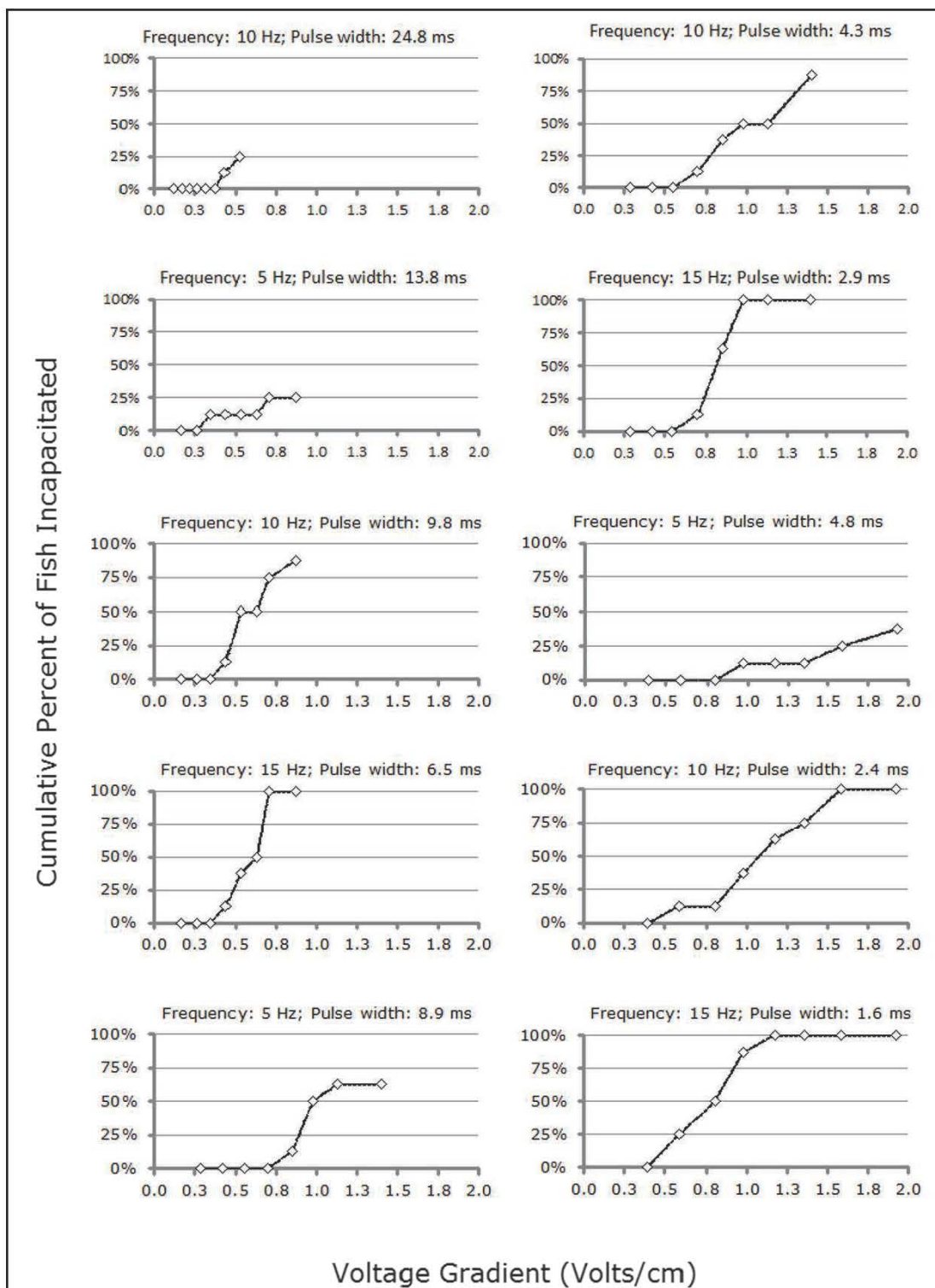


Figure 7. The cumulative percent of silver carp incapacitated during electrical exposures as a function of field strength (V/cm). Data from 80 fish are represented, eight fish per treatment group.

Large bighead carp (> 500 mm) were reported as being very sensitive to electric fields (Dettmers and Pegg 2003). It is well established (in the context of capturing wild fish with electricity) that the reactions of fish to electrical exposure are often size dependent (Sternin et al. 1976; Miranda 2009). The phenomenon of larger fish having lower thresholds of response to a given electric field than smaller fish is significant and attributed to bigger fish intercepting a greater difference in electrical potential than smaller fish. Therefore, the recommended protocols in this study for fish greater than 200 mm total length will not be as effective for smaller fish.

The orientation of the electric field (i.e., direction of electric current flow) generated by electric barrier systems can strongly influence the risk of failing to immobilize fish penetrating the field. Electrical exposure (and the likelihood of immobilization) is maximized when fish are oriented parallel to the direction of electric current flow and minimized when fish are perpendicular. The electric barriers in the CSSC employ cross-channel electrodes, ensuring maximum exposure to fish swimming upstream, into the flow (water and electric current). Thus, the simulations of encroachment were conducted under a condition of no (or minimal) water current flow, allowing fish opportunities to minimize electrical exposure by turning perpendicular to the direction of current flow. Allowing voltage-minimizing behaviors during the simulations provides conservative estimates of field parameters resulting in immobilization.

The present study was the first step in a comprehensive evaluation of operating protocols for the electric barriers on the CSSC for deterrence of small invasive carp. Outcomes of the experiment demonstrate there is some latitude in the selection of operational protocols, as several combinations of electrical parameters were shown capable of blocking the passage of small silver carp through the electric barriers. Operational protocols and electrical settings effective on small fish can be expected to be even more effective on larger fish.

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